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## Smear zone characterization associated with vertical drain installation

### Abstract

In this study the characteristics and extent of the smear zone were investigated using a undisturbed sample. The aim was to capture the realistic characteristics of the smear zone in relation to the in-situ structure of soil during the installation of prefabricated vertical drain (PVD) using a steel mandrel. The extent of the smear zone for Bulli clay was determined on the basis of normalised permeability ( $k_h/k_{hu}$ ) and a reduction in the water content upon consolidation. The permeability and compressibility of the soil were investigated to determine the extent to which the soil surrounding the PVD had become disturbed.

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## **SMEAR ZONE CHARACTERIZATION ASSOCIATED WITH VERTICAL DRAIN INSTALLATION**

Cholachat Rujikiatkamjorn<sup>1</sup>, Buddhima Indraratna<sup>2</sup> and Made Dodiek Wirya Ardana<sup>3</sup>

**ABSTRACT:** In this study the characteristics and extent of the smear zone were investigated using an undisturbed sample. The aim was to capture the realistic characteristics of the smear zone in relation to the in-situ structure of soil during the installation of prefabricated vertical drain (PVD) using a steel mandrel. The extent of the smear zone for Bulli clay was determined on the basis of normalised permeability ( $kh/k_{ho}$ ) and a reduction in the water content upon consolidation. The permeability and compressibility of the soil were investigated to determine the extent to which the soil surrounding the PVD had become disturbed.

**Keywords:** Disturbance, Soft Soils, Vertical drains

### **INTRODUCTION**

In-situ soils usually possess a distinctive structure, whose behaviour is different from the same material in a reconstituted state (e.g., Burland 1990; Leroueil and Vaughan 1990; Cuccovillo and Coop 1999). There have been a lot of studies on developing constitutive models that consider the structure of the soil, such as those proposed by Gens and Nova (1993), Whittle (1993), Wheeler (1997), Rouainia and Muir Wood (2000), and Liu and Carter (2002). Liu and Carter (2002) proposed a new constitutive model for structured clays where its parameters can be readily determined in the laboratory.

Prefabricated vertical drains (PVDs) have commonly been employed to speed up the consolidation. In this process PVDs are inserted into the clay foundation with a track mounted crane and a steel mandrel that houses the drain and its anchor. The installation of drains causes a disturbed zone around them, which is known as smear zone, where the structure of the clay is changed such that the lateral permeability is decreased and compressibility is increased, which lengthens the time required for the soil to consolidate. The parameters required to distinguish the smear zone are the smear zone radius,

and the ratio between the horizontal coefficients of permeability (Chai and Miura, 1999). Using reconstituted soils, Onoue et al. (1991) described the variation of the horizontal coefficient of permeability through laboratory experiments and proposed a three zone model for any variation in permeability around a drain. Indraratna and Redana (2000) approximated the smear zone to be 4 – 5 times bigger than the equivalent radius of the drain and the horizontal to vertical permeability ratio to approach unity in the smear zone. Hird and Moseley (2000) determined the characteristics of the smear zone in multi-layered and then proposed an inner smear zone radius of three times the equivalent radius of the drain. Based on large scale laboratory tests, Sharma and Xiao (2000) and Ghandeharioon et al. (2010) concluded that the smear zone is about 4 times the equivalent diameter of the drain and 3.1 times the equivalent diameter of the mandrel, determined using elliptical cavity expansion theory, respectively. In previous studies, an estimation of the smear zone was mainly based on laboratory testing using reconstituted (remolded) soil, where its structure was fully or partially destroyed during preparation. In recent years, researchers and practitioners have shared the difficulties associated with estimating the smear zone of in-situ soil (Bo et

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al. 2003, Chu et al., 2000). Indraratna and Redana (2000) proposed a preliminary analytical and numerical model to capture the effect of the smear zone, but the role played by the structure of the soil was not properly captured. However, as the above findings were based on testing reconstituted soils, none of these approaches correctly captured the role of the soil structure; hence the corresponding deformation and excess dissipation of pore pressure associated with soft clays subjected to radial consolidation may not accurately represent the actual behavior.

In this paper, a large undisturbed sample was obtained to assess the altered soil properties such as permeability and compressibility in the smear zone after the installation of prefabricated vertical drains. The aim was to capture the more realistic characteristics of the smear zone with the structure of the soil intact. The de-structuring of clay during installation was assessed through changes in the void ratio, permeability, and compressibility. A consolidation test was conducted on the large sample, and then the smear characteristics were evaluated using small specimens cored at various locations.

Compression behavior of reconstituted and structured soils

The structure of the soil can normally be measured using the variation in the void ratio obtained from compression tests. Liu and Carter (1999) discussed how the behaviour of a structured soil differs from the same soil in a reconstituted condition in at least three ways: (1) intact structure represents a material that is initially stiff or at relatively low stress levels, (2) soil with structure sustains a higher void ratio than a corresponding reconstituted soil, and (3) during virgin yielding, a structured soil is generally more compressible than a reconstituted soil, but it moves closer to becoming a reconstituted soil as de-structuring progresses.

A material idealisation of the isotropic compression of structured and reconstituted soils during virgin compression is shown in Figure 1 with a variation of the void ratio due to de-structuring during compression (Liu and Carter, 1999, 2000). The complete expressions for the reconstituted and structured soil curves in Figure 1 are given as follows:

$$e^* = e_{ic}^* - \lambda^* \ln p' \quad (1)$$

$$e = e_{ic}^* + \Delta e_i \left[ \frac{p'_{y,i}}{p'_s} \right]^b - \lambda^* \ln p' \text{ for } p'_s \geq p'_{y,i} \quad (2)$$

where  $e^*$  is the void ratio of reconstituted soil during isotropic compression;  $e_{ic}^*$  is the void ratio of reconstituted soil when  $p' = 1$  kPa during virgin isotropic compression;  $\lambda^*$  is the gradient of isotropic compression line (ICL) of the reconstituted soil;  $e$  is the void ratio of undisturbed (structured) soil;  $\Delta e_i$  is the difference in the void ratio between structured and reconstituted soil at the initial yield point;  $p'_{y,i}$  is the value of the mean effective stress at the initial yield point;  $p'_s$  is the value of the current structural yield surface;  $p'$  is the current mean effective stress; and  $b$  is a parameter representing the rate of de-structuring.

The destructuration of clay was also explained by Leroueil, et al. (1979). A pair of consolidation tests were performed on intact and destructured samples of Saint Alban Clay to study the volumetric deformation against the mean effective stress. The results showed that the path from a natural state (structurally intact) to a destructured state when loaded beyond its preconsolidation pressure, causes significant changes to the behaviour of the soil. It was also mentioned that modifications to the behavior of soil included the shape and position of its limit state curve, the values of shear and compression moduli in the over consolidated states, the mode of pore pressure generation, and the associated peak and large strain shear strengths.

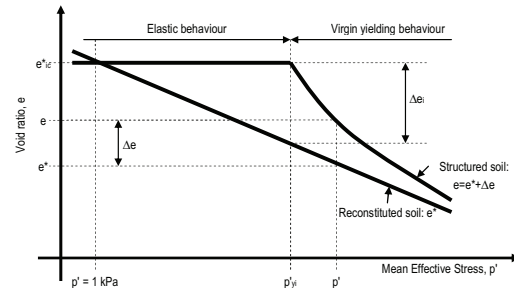


Figure 1. Idealisation of the compression of reconstituted and structured soils (after Liu and Carter, 2002)

## LARGE SCALE CONSOLIDOMETER

A schematic diagram of the modified large scale consolidometer is given in Figure 2, following the original design by Indraratna and Redana, (1998). The consolidometer consists of three main parts; (1) the cylinder which can be used as a corer to obtain an undisturbed sample and serve as a rigid boundary during consolidation, (2) the loading rig platform, and (3) the pneumatic air pressure chamber. The cylindrical tube (corer) was made from 5mm thick steel plate rolled to form two half cylinders, each with a 345 mm internal diameter by 700 mm long. To minimise disturbing the sample during the retrieval

stage, the dimensions of the corer were designed on recommendations made by Hvorslev (1949).

The specially designed sleeves on both ends of the half cylinder corer form a perfect cylinder. A Teflon film was sprayed all over the surface of the inner wall to reduce friction between the soil and the wall during coring and consolidation. The cylinder can be fitted with top and bottom caps. The top cap was made from 6 mm thick steel plate and was designed to be stiff enough during retrieving to ensure that the sample remained undisturbed. Both caps have three drainage valves that can be opened or closed during sampling and testing. A 342 mm diameter stainless steel piston was placed on top of the sample to ensure that the load from the pneumatic air pressure chamber was distributed uniformly, and to ensure uniform vertical deformation during consolidation. To prevent water from leaking past the piston, there are two grooves around its periphery for two 5 mm diameter o-rings.

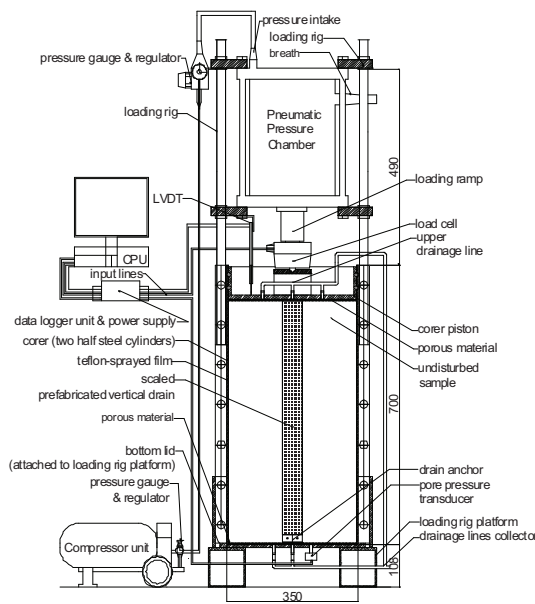


Figure 2. Large-Scale Consolidometer (unit: mm) (Rujikiatkamjorn et al. 2013)

#### RECOVERY OF UNDISTURBED SAMPLE

The samples of undisturbed soil used in this experiment were obtained from a site at Bulli, New South Wales, Australia. The physical properties of the soil are given in Table 1. Based on the Unified Soil Classification System, the soil was classified as inorganic clay with high plasticity (CH). These samples were retrieved from the site with a light excavator which pushed the corer into the cleared surface at the required depth. The top cap was attached to the corer to prevent the sample from moving and from losing moisture. The reason for

pushing the corer with a steady force was to maintain a continuous and uniform motion and thus minimise the degree of disturbance. The static push method described above prevents any rotation and is a recommended and longstanding technique for obtaining quality samples (Hvorslev, 1949). In this study the sampling depth was approximately 2 m from the surface. Afterwards, the soil surrounding the corer was excavated and a sample was cut from the bottom of the pit. The samples were sealed at the base to prevent any loss of moisture. The top cap and end cap were placed on the top and bottom of the sample to ensure there was no air gap at the interfaces between soil and the caps, and to prevent any further stress relief. The samples were kept in a humidity controlled room before testing.

Table 1. Some physical properties of Bulli Clay

Properties	Values
Liquid Limit, LL (%)	50
Plastic Limit, PL (%)	25
Plasticity Index, PI	25
Specific Gravity, Gs	2.62
Water Content, (%)*	41.4
Void Ratio, e*	1.13
Wet Unit Weight (kN/m <sup>3</sup> )*	18.5

\*) obtained from small size undisturbed sample

#### TESTING PROGRAM

The lower part of the cylindrical sample was docked on the bottom platform and the upper part was attached to a specially designed loading rig. A load cell was placed between the piston and the pneumatic air pressure chamber, and an axial displacement transducer was installed on top of the piston to measure vertical settlement. The applied load and settlements were recorded using a data logger. Although the cylinder was relatively large, and to avoid disturbing the sample any further, instruments such as the miniature pore pressure transducers were not installed inside the sample. A hollow rectangular mandrel made from 1.5 mm thick stainless steel plate was used to install a scaled down band shaped drain. The mandrel was 5 mm thick and 55 mm wide, which provided an equivalent mandrel radius ( $r_m$ ) based on 16.2 mm. A rectangular drain anchor with the same cross section as the mandrel

was also attached to the drain prior to installation. The single band shaped (rectangular cross section) prefabricated vertical drain consists of a non-woven synthetic geotextile material surrounding a plastic core. The width of the drain was scaled down to 50 mm ( $r_w = 13.5$  mm) due to the size of the sample. Installation of the drain was completed by manually pushing the mandrel vertically into the sample at a constant speed, and then withdrawing immediately after it reached the base. A mandrel guide was also used to ensure that the PVD was installed along the centerline of the specimen.

Two experimental series, i.e. Series A and B, were subjected to different maximum applied pressures of 50 kPa and 200 kPa, respectively. Both series were subjected to a pre-consolidation pressure of 20 kPa that represented the in-situ vertical effective stress. With Series A, an additional vertical stress of 30 kPa was applied, and with series B, a three loading stages were applied in order to achieve a total pressure of 50 kPa, 100 kPa, and 200 kPa. The test was carried out in 3 phases: (1) preparation of the sample and loading rig, (2) installation of the prefabricated vertical drain and consolidation test, (3) small sample (specimen) coring for the moisture content test and oedometer test. In the first phase, the large scale undisturbed sample was assembled on the loading rig platform. The drainage valves on the piston and base were both opened to collect any excess water. In this phase a vertical consolidation pressure of 20 kPa was applied to simulate the in-situ effective stress.

In the consolidation phase, after the application of preconsolidation pressure, the piston was removed from the sample. A mandrel guide was bolted onto the top of the sample to ensure that the mandrel was installed vertically, and then the piston was placed on top of the sample. Vertical consolidation pressures were applied to the sample in accordance with the test series, until the primary consolidation process was complete. The vertical displacement curve that occurred while the consolidation pressure for the B-series sample was being applied is plotted in Figure 3.

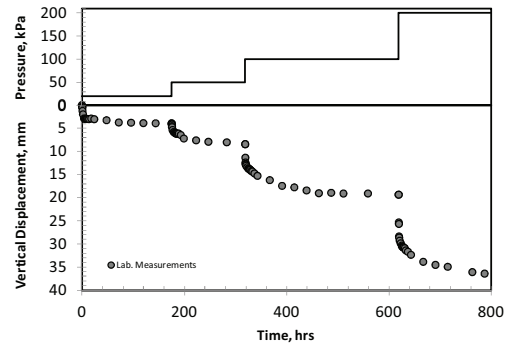
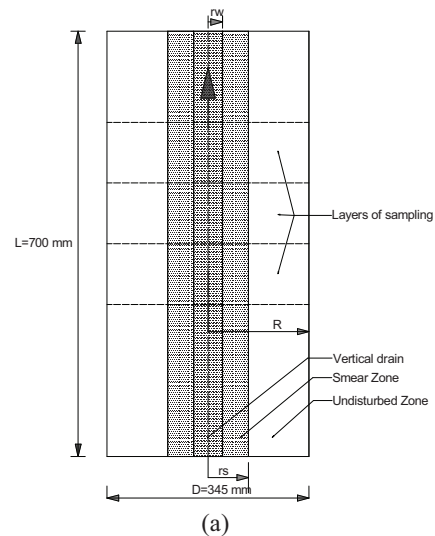


Figure 3. Vertical displacement curve versus time for B-series large sample (Rujikiatkamjorn et al. 2013)

After the primary consolidation process had been completed, the cell was split into two parts to enable specimens to be collected from various locations. The horizontal and vertical specimens obtained from two layers at a certain depth are shown in Figure 4(a). The specimen prepared for the oedometer test was 50 mm diameter by 20 mm thick. The oedometer tests were conducted to obtain the compressibility and permeability of the clay specimens. Five specimens were obtained from each layer, at a certain distance from the centre of the drain, for the D-axis and A-axis, as shown in Figure 4(b). The D-axis samples were collected along the width of the drain and the A-axis samples were collected along the thickness of the drain. At the same time, moisture content tests were conducted at the same locations. The three layers selected for sampling were 450 mm, 350 mm, and 250 mm from the base. The small horizontal samples (4H, 3H, 2H, 1H and 0H) were collected at 140 mm, 90 mm, 60 mm, 30 mm, and 0 mm radial distances from the centre of the drain.





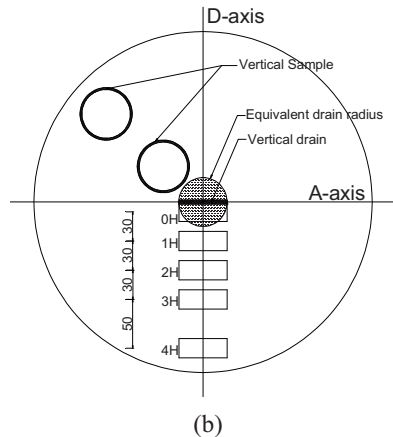


Figure 4. (a) Unit Cell showing the layers of sampling; (b) Schematic cross section of small sampling locations for oedometer test (Rujikiatkamjorn et al. 2013).

## TEST RESULTS AND ANALYSIS

### *Characterization of the Smear Zone based on the Moisture Content, Void Ratio, and Permeability*

The variations in moisture content at radial distances for the B series samples are shown in Figure 5. The variation in moisture content for the D-axis and A-axis samples were influenced by the installation of the drain within a radius of 60 – 90 mm from the centre. Based on these curves, the radius of the smear zone can be estimated to be 60 mm. Figure 6 shows the variation of the void ratio from horizontal specimens collected from both large scale samples. The distribution of the void ratio in a radial direction shows the void ratio reduced further in the region adjacent to the drain (0 – 60 mm). There was a significant drop in the void ratios in this region (radius of smear zone = 60 mm) which is approximately 3.7 times the equivalent mandrel radius ( $r_m$ ), so this region can be considered as a representation of the smear zone. Outside this zone, the void ratios tended to have a relatively constant value at a distance of more than 60 mm towards the boundary of the sample. Figure 6 also shows the variation of horizontal permeability in the radial direction. The permeability curves show a similar trend to the void ratio and moisture content where permeability close to the drain was lower in those samples further away from the drain. Permeability beyond a radius of 60 mm tends to have a constant value. The estimated extent of smear based on the variations in permeability agrees well with those based on both the moisture content and void ratio. In the area beyond 90 mm from the centre, disturbance in the soil was found to be minimal. It was clear there were two disturbed zones surrounding the drain

which were either completely disturbed or marginally disturbed. Onoue et al. (1991) and Madhav et al. (1993) also divided the smear zone into two sub-zones: an inner zone with highly disturbed soil and an outer transition zone where the disturbance gradually decreases as the distance from the centre of the drain increases.

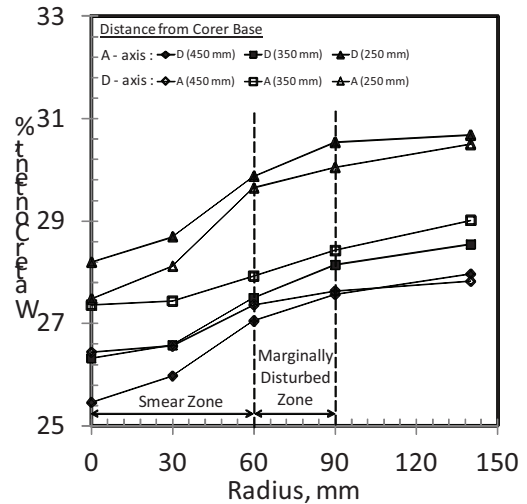


Figure 5 Moisture content figure of B-series samples (Rujikiatkamjorn et al. 2013).

Figure 6 also presents the change of normalised horizontal permeability ( $k_h/k_{hu}$ ) along the radial distance for both large scale samples with maximum consolidation pressures of 50 kPa and 200 kPa. The horizontal permeability of the large scale sample in the region that is 60 mm from the centre is approximately 50% - 80%, which is an average of 65 % lower than in the undisturbed zone. Indraratna and Redana (1998) provided normalised permeability (horizontal and vertical permeability) of reconstituted soil for the range of mean consolidation pressures between 6.5 kPa to 200 kPa. In the disturbed zone approximately 100 mm from the centre of the drain, the reduction in permeability was approximately 22% - 48%, which is an average of 35% lower than in the undisturbed zone. Sathananthan and Indraratna (2006) conducted a radial consolidation test using a reconstituted soil with a similar range of consolidation pressures (25 – 250 kPa) and showed a similar result for normalised horizontal permeability ( $k_h/k_{hu}$ ). The radius of the disturbed zone was 78.75 mm and the reduction in permeability was approximately 40% lower than in the undisturbed zone.

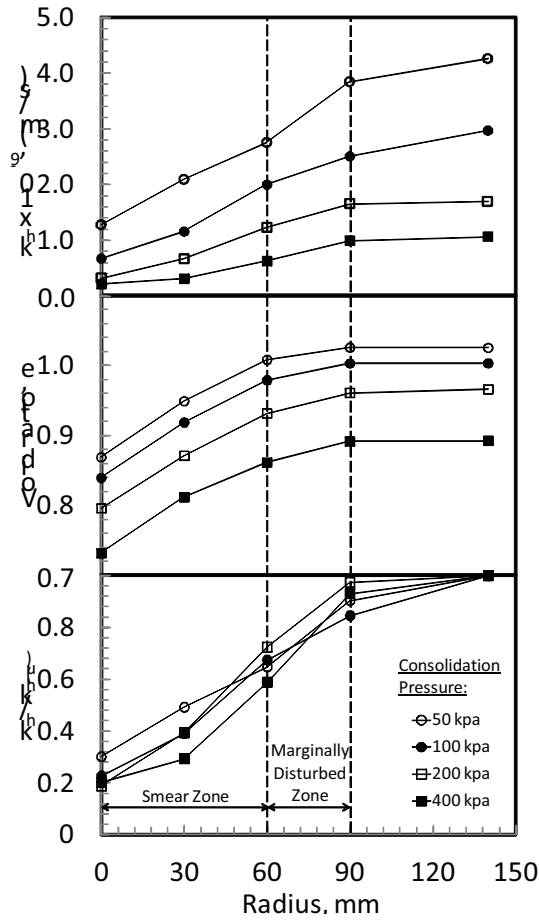


Figure 6. Radial distribution of horizontal permeability, void ratio, and normalised permeability of A-series and B-series (Rujikiatkamjorn et al. 2013).

Similar work by Sharma and Xiao (2000) indicated that the ratio of normalised permeability in the disturbed zone was 22% - 42%, with an average of 32%. It can be seen that the aforementioned studies using remolded soil resulted in similar reductions in permeability in the disturbed zone, which is lower than the reduction in permeability obtained from this study using undisturbed samples. The use of a large undisturbed sample indicated the larger reduction in permeability in the disturbed zone was almost twice that in the remolded sample. These differences in the permeability of the undisturbed sample can be almost ten times greater than the corresponding values for the disturbed sample.

#### Determination of Soil Disturbance Due to Drain installation

Soil destructuration can occur while samples are being retrieved or drains are being installed by the steel mandrel. The degree of disturbance can be quantified using the compression curves (Schmertmann, 1953; Nagaraj et al, 1990; Shogaki,

1996; Hong and Onitsuka, 1998; Nagaraj et al, 2003; Prasad et al, 2007). Most specimens with some degree of disturbance will show a compression curve that falls in between the compression curves of the undisturbed and completely remolded samples (Rutledge, 1944). Therefore, a structured soil represents an ideal condition for insignificant disturbance while a reconstituted soil represents a disturbed soil, or the condition of destructuration. In view of the above, a conceptual model to evaluate the degree of disturbance in relation to the soil structure is proposed using the compression curves shown in Figure 7 and the conceptual description given below.

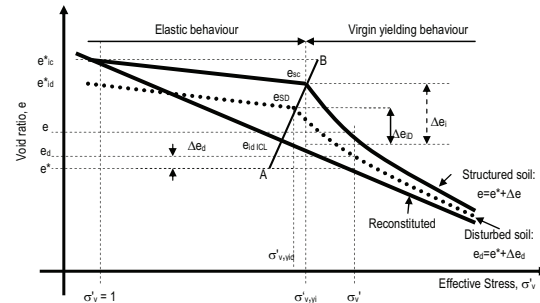


Figure 7. Proposed concept to evaluate the degree of soil disturbance (Rujikiatkamjorn et al. 2013).

1. The compression curves of partially disturbed soil can be obtained by plotting the various void ratios against the mean effective stress. It is assumed that the yield stress of the partially disturbed soil is located on the extrapolation of the line AB (Fig. 6) through the yield stress points intersecting the horizontal line from the in-situ void ratio. This line is perpendicular to the intrinsic state line (Nagaraj. et.al., 1990).
2. Based on the concept of a Structured Cam Clay Model, in the elastic behaviour region. The laboratory testing in this study was carried out under one dimensional conditions, and the original parameters  $\lambda$ ,  $\kappa$ , and  $p'$  were substituted with  $C_e$ ,  $C_s$ , and  $\sigma'_{v,i}$ , respectively.
3. Line **AB** can be constructed to obtain the loci of yield stress for the partially disturbed soil. The proposed line where the yield stress points locate is the line through point B of the value of the initial yield stress ( $\sigma'_{v,y,i}$ ) of the structured soil and the perpendicular intersect of the ICL of the reconstituted soil at point A

A small sample of undisturbed clay and a remolded sample were tested using conventional oedometer apparatus to set up the boundaries of the virgin undisturbed curve and the remolded curve. The specimens cored along the radial distance from



the centre of the drain considered to be partially disturbed, were also tested with the oedometer apparatus. Figure 8 shows the plots of various void ratios with the effective stress of the partially disturbed soil for the A-series and B-series. It can be seen that the soil became increasingly disturbed towards the drain as the soil adjacent to drain experienced severe remolding due to the drain being installed. The plots of the experimental data and the model predictions are in good agreement.

In relation to the curves plotted in Figure 8, an attempt to quantify the degree of disturbance to the soil is now presented. Figure 9(c) shows the degree of disturbance of soil structures against the radial distances after the drain was installed. The surrounding soil adjacent to the drain has a higher degree of disturbance. Based on the model predictions for the relatively undisturbed region, the degree of disturbance can still be approximately 19 % and 22% for the A-series and B-series samples, respectively. Disturbance could also occur as a result of coring smaller specimens from the large samples. In the disturbed region (a smear zone), the degree of disturbance was approximately 32% under a consolidation pressure of 50 kPa. For the B-series samples subjected to a higher consolidation pressure of 200 kPa, the degree of disturbance in the disturbed zone was approximately 20% higher than in the undisturbed zone.

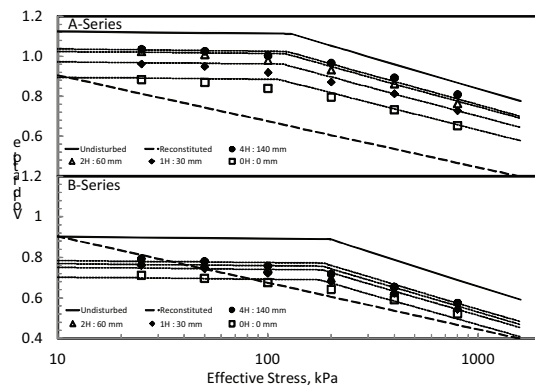


Figure 8. Void ratio of partially disturbed soils (Rujikiatkamjorn et al. 2012).

## CONCLUSIONS

These tests were carried out on a large scale undisturbed sample of Bulli Clay, New south Wales, Australia that had been tested on a specially designed large scale consolidometer. Two large samples were consolidated with consolidation pressures of 50 kPa and 200 kPa prior to tests conducted on small cored samples in a conventional oedometer. Data from the tests were analysed to establish the characteristics of the smear zones and prediction of disturbance due to

the soil being de-structured in the smear zone. The extent of the smear zone was estimated on the basis of normalised permeability ( $k_h/k_{hu}$ ) and change in the water content. The smear zone and the marginally disturbed zone were found to be about 3.7 times and 5.5 times the equivalent radius of the mandrel, respectively. The 50% - 80% drop of normalised permeability in the disturbed zone was significant in that it was a larger drop in value than similar works which resulted in lower values of 32% - 40% when remolded soil was used. The degree of soil disturbance in the disturbed zone was approximately 20% to 32% higher than that in the undisturbed zone. It was clear that the soil lost a significant amount of its structure after the drain was installed, especially in the region close to the drain. When the soils were disturbed, the permeability, coefficient of consolidation and coefficient of volume change values, decreased. Therefore, based on this finding, the variation of soil compressibility with radius needs to be taken into account during design apart, from the variation of soil permeability.

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